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Nuclear Effects in High Energy Antineutrino Interactions

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Abstract

Backward protons from neutrino and antineutrino interactions in the Ne-H_2 mixture are studied. The inclusive characteristics of the reactions are presented for both neutral and charged current events and comparison with models are made. The data are in agreement with the hypothesis of nuclear scaling.

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1. Introduction

A large number of experiments of the type

$$h(\gamma) + A \rightarrow (\pi^{\pm}, p, D, \cdots) + X$$

have been performed to study the collective behavior of the nucleons in the nuclear target (A)[1]. In these experiments the final state particle ($\pi^{\pm}$,p,D, ...) travels backward relative to the beam direction in the laboratory system. Since the observed backward protons cannot originate from interactions on free stationary nucleons they indicate the presence of nuclear effects in the scattering process.

The inclusive spectrum of backward protons can be parameterized with an exponential

$$\frac{E}{p} \frac{d\sigma}{dp^2} = C \exp(-Bp^2) \qquad (1)$$

where E and p are the energy and momentum of the proton in the laboratory system. The slope (B) does not depend on the energy of the primary particle and is insensitive to the mass of the target nucleus. The absolute scale (C) depends only weakly on the incident energy. These experimental findings have led to the hypothesis of nuclear scaling.[1] It has been suggested that reactions of this type provide direct information on the high momentum part of the nuclear wave function.[2,3,4]

2. Models

In a model based on short range correlations amongst the nucleons (SRO) the backward protons are viewed as manifestations of two, three, or four nucleon clusters which have high relative momenta inside the target nuclei.[2] In the kinematical domain available for our analysis two-nucleon 'clusters' should dominate. In this model the incident neutrino interacts with a nucleon which has its momentum vector oriented in the forward direction. The neighboring spectator nucleon is then thought to travel in the opposite (backward) direction. The SRO model predicts smaller average Bjorken x[5] for these events due to smaller available center-of-mass energy of the interaction (similar to a Doppler effect), i.e.

$$x = x'(2-\alpha) \qquad (2)$$

where x' is the corresponding x-value for an interaction on a stationary free nucleon, and $\alpha = (E_p - p_{\parallel})/m$ with E_p, m and $p_{\parallel}$ the proton energy, mass, and longitudinal momentum respect to the "current" direction.

A second model assumes an initial "prepared" state of the nucleus with a fast backward nucleon whose momentum is balanced by the rest of the nucleons.[3,4] Deep inelastic scattering then occurs off the fast backward oriented nucleon with a momentum transfer that is so small that the struck nucleon does not change its orientation but emerges into the backward hemisphere in the laboratory system. This picture leads to a substantially smaller average x, Q^2 and charged multiplicity for these events as compared to the overall data sample.

A similar model of the target nucleus is adopted in Ref. 6 but in this case the interaction is thought to proceed off the bulk of the nucleus which balances the momentum of a fast single nucleon. This picture does not assign any specific features to the events with backward protons.

Finally, in the multiple rescattering model backward protons are thought to result from several successive rescattering processes of a nucleon in this nucleus.[4] No significant effects in the x or Q^2 are foreseen.

3. Experimental Details

In this paper we present the results of a detailed study of nuclear effects in neutrino- and antineutrino-neon interactions. The data comes from a 155,000 picture exposure of the Fermilab 15-ft. bubble chamber filled with a heavy Ne-H_2 mixture (64 atomic % Ne). The chamber was exposed to a wide-band antineutrino beam from 400 GeV/c incident protons. A comparison with neutrino events is permitted by the inclusion of the sample of ν-Ne charged current interactions recorded as a background in the same experiment. Further experimental details are given in Ref. 8. The present analysis represents an upgraded investigation of the subject originally reported in Ref. 8 based upon a five-fold increase in the sample size. The improved statistics also enable us to study nuclear effects in neutral current interactions. The neutral current event sample consists of events in which the fastest charged track does not leave the chamber and for which no muon candidate is found by the External Muon Identifier. The charged current contamination in this sample is estimated to be less than 30% which is adequate for the purpose of the following analysis. The neutral current event selection procedure does not allow us to distinguish between neutrino and anti-neutrino induced neutral current events. For each of the three data samples: $\bar{\nu}Ne \to \mu^+ x$, $\nu Ne \to \mu^- x$, $\bar{\nu}(\nu)Ne \to \bar{\nu}(\nu)+x$ we identify an event as a backward proton (BP) event (2 backward protons (2BP) event) if there is one track (two tracks) emerging backward in the laboratory and stopping in the chamber with neither a decay nor interaction and having a momentum in the range 0.2 to 0.8 GeV/c. We found only 3 events with three backward protons and they have been treated as 2BP-events. We made corrections for protons which interact and are misidentified as π^+'s. These corrections result in ~ 10% growth of relative yields and a small decrease (smaller than statistical errors) of fitted slope parameter B in (1).

4. Results

The total numbers of events and relative yields are summarized in table 1 (corrected values are given). Within our statistics the yields are equal for all three samples. Invariant proton spectra were fitted according to equation (1). The 2BP events entered the distributions twice. Results for the three samples are shown in Fig. 1a, b, c. We obtain the following slope parameters (for the momentum interval $0.3<p<0.7$ GeV/c):

$$B(CC,\mu^{+}) = 10.7 \pm 0.7,$$
$$B(CC,\mu^{-}) = 10.4 \pm 1.8,$$
$$B(NC) = 10.5 \pm 1.6.$$

These values are all consistent and are in good agreement with our earlier data published in [8]. They also fit well into the nuclear scaling hypothesis (see comparison with hadronic data in [8]).

The azimuthal angular distributions (not shown) are consistent with being isotropic. The distributions in $\cos\theta_p$ (θ_p is the angle between the proton momentum vector and the neutrino beam direction) are shown in Fig. 2. The growth of the proton momentum leads to a sharp anisotropy of the $\cos\theta_p$ distributions.

Mean values of the total charge $\langle c \rangle$, total multiplicity $\langle n \rangle$ and $\langle Q^2 \rangle$ for events with backward proton(s) and for the rest of the charged current neutrino and antineutrino samples are compared in table 2. We also show mean values of v ($v = E_\mu(1-\cos\theta_\mu)/m$, E_μ and θ_μ are the muon energy and angle). As seen from table 2 for both the ν and the $\bar{\nu}$ samples there is a significant difference in $\langle n \rangle$ and $\langle c \rangle$ between the samples with backward proton(s) and without it. This difference partially follows from the definition of the BP-samples.

In the framework of the pair correlation mechanism[2] it is predicted that

$$\langle y \rangle_\alpha = \langle y \rangle, \langle v \rangle_\alpha = (2-\alpha) \langle v \rangle \qquad (3)$$

for $1.3 \leq \alpha < 2$ where $\langle y \rangle$ and $\langle v \rangle$ are mean values for the CC-sample and $\langle y \rangle_\alpha$ and $\langle v \rangle_\alpha$ are mean y and v for BP events with given value of α.

Fig. 3a, b shows the results of a comparison of the $\langle v \rangle_\alpha$ and $\langle y \rangle_\alpha$ dependences in α for BP events[9] with a prediction of the pair correlation scheme[2] obtained using an equation (3) and the total sample of the antineutrino charged current events (solid line).

Fig. 4a, b illustrates the analysis of correlations between the two protons in 2BP-events. For this purpose we compared the distributions in the invariant mass of the two protons M_{pp} and $\cos\theta_{pp}$ (where θ_{pp} is the angle between protons), with similar distributions for two proton tracks taken from independent BP-events (which are therefore uncorrelated). There is no apparent correlation. The absence of an enhancement near $\theta_{pp}=90^{\circ}$ (Fig. 4b) does not support the picture in which one backward proton elastically scatters another proton out of the nucleus.

5. Conclusion

We have studied samples of ν and $\bar{\nu}$ induced events, which contain protons in the kinematical region forbidden for interactions off stationary free nucleons. Inclusive properties of these events were investigated for neutrino and antineutrino charged current samples and for the neutral current sample. A qualitative check of the pair correlation model was performed and an agreement with the data was found. A correlation analysis of events with two backward protons was made. A comparison of the deep inelastic features of the events with backward proton(s) and the entire charged current sample shows that neither of the mechanisms mentioned above can provide a complete description of the observed nuclear effects.

References

[1] G.A. Leksin, Proc. of the XVIII Int. Conf. on High Energy Physics, Dubna, 1977.
A.M. Baldin et al., Communications of the Joint Institute for Nuclear Research, Report No Dubna-11302, 1978.
N.A. Burgov et al., Report No ITEP-147, 1978.
Yu.D. Baiykov et al., Report No ITEP-6, 1979.

[2] L.L. Frankfurt, M.I. Strikman, Phys. Lett., 69B, 93, 1977.

[3] S. Frankel, Phys. Rev. Lett., 38, 1338, 1977.

[4] R.D. Amado, R.H. Woloshyn, Phys. Rev. Lett., 36, 1435, 1976.

[5] The scaling variables are defined by $x=Q^2/2m\nu$ and $y=\nu/E_\nu$ where Q^2 is the square of the four-momentum transfer, ν is the energy transfer to the hadrons in the laboratory system, and m is the mass of the nucleon.

[6] H.J. Weber, L.D. Miller, Phys. Rev., C16, 726, 1977.

[7] B.Z. Kopeliovich, Yad. Phys., 26, 168, 1977.

[8] J.P. Berge et al., Phys. Rev. D18, 1367, 1978.

[9] Figs. 3 and 4 are plotted for the BP and 2BP events in the antineutrino charged current sample which is the only one having sufficient statistics for such an analysis.

Table I

Total numbers of events and relative yields.

	Charged current anti-neutrino	Charged currents neutrino	Neutral currents
Total sample	4053	611	1018
BP+2BP events	402	73	106
2BP events	52	11	10
(BP+2BP)/Total	0.10±0.01	0.12±0.04	0.10±0.01
2BP/(BP+2BP)	0.13±0.02	0.15±0.05	0.09±0.03

Table II

Comparison of events with backward proton(s) with the rest of the charged current samples.

Variable	(BP+2BP)$_{\bar{\nu}}$	(CC-BP-2BP)$_{\bar{\nu}}$	(BP-2BP)$_{\nu}$	(CC-BP-2BP)$_{\nu}$
$\langle c \rangle$	2.9±0.1	1.2±0.0	2.0±0.2	0.7±0.1
$\langle n \rangle$	8.7±0.2	7.3±0.1	11.1±0.6	9.0±0.2
$\langle Q^2 \rangle$	3.4±0.3	4.2±0.1	8.2±0.5	8.7±0.3
$\langle v \rangle \times 10^3$	59±3	74±1	85±8	90±3

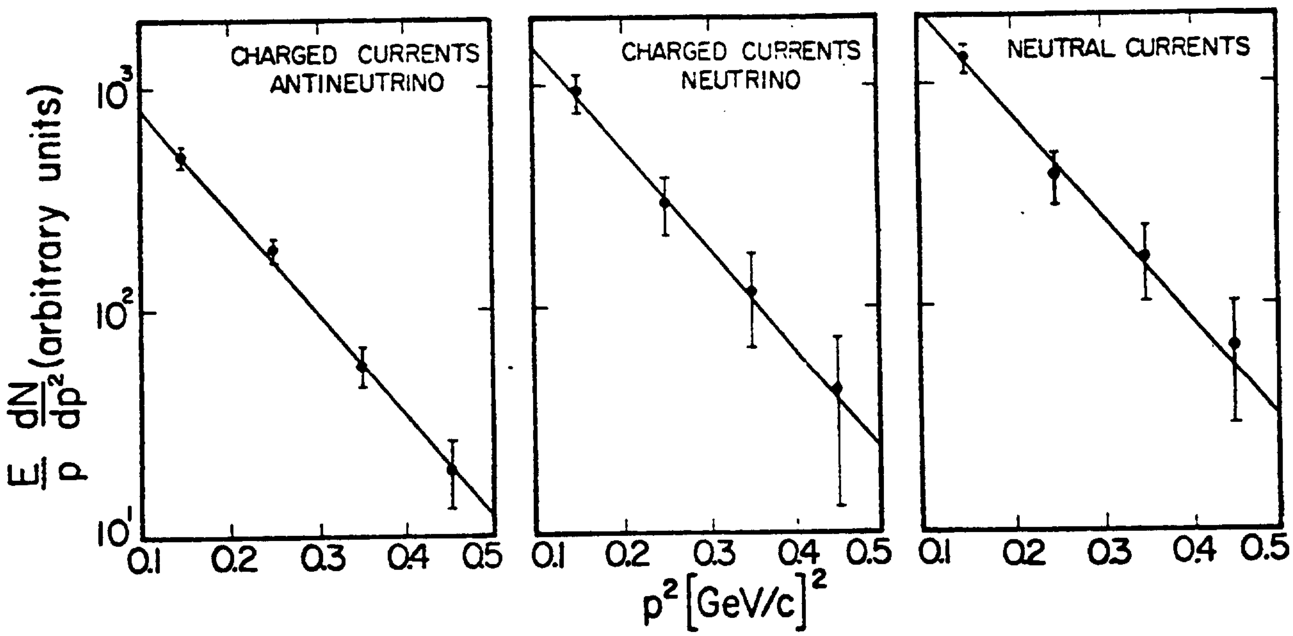

Fig. 1. Inclusive spectra of the backward protons for charged current antineutrino (a), neutrino (b) and for neutral current events (c). Solid line is a fit to formula (1) (see the text).

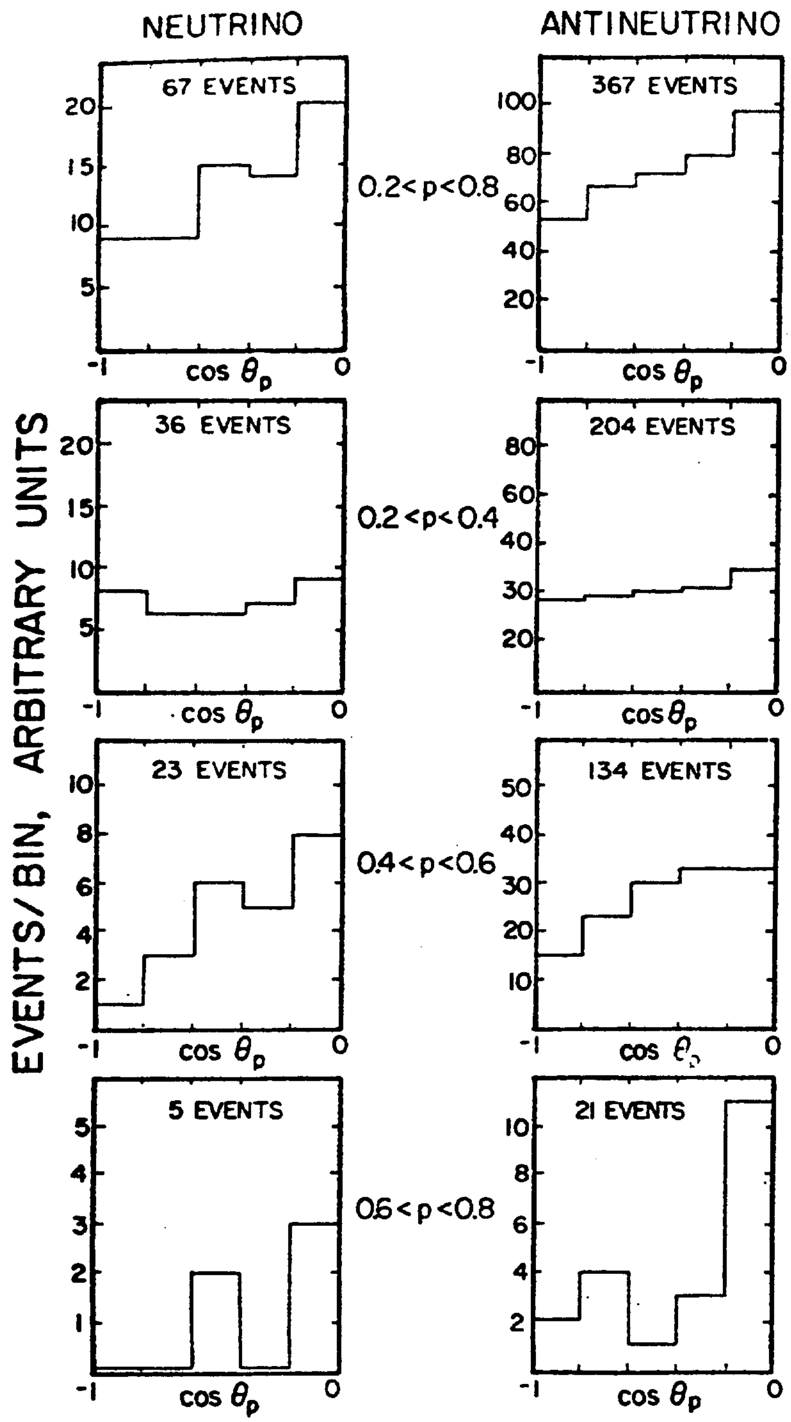

Fig. 2. Distributions in $\cos\theta_p$ for the antineutrino and neutrino BP-events. The distributions are given for the entire BP-samples (two uppermost) and for three intervals of the proton momenta.

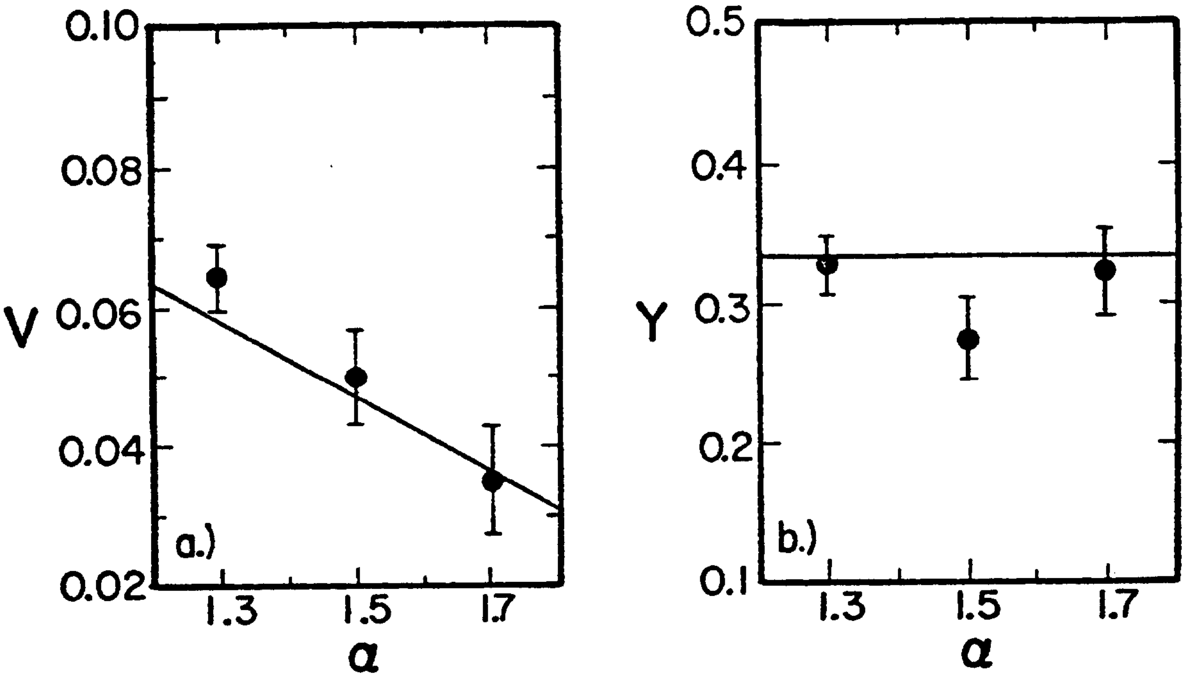

Fig. 3. Comparison of this experiment with predictions of the pair-correlation model[2]. Solid lines correspond to α-dependence of the scaling variables v and y given in [2].

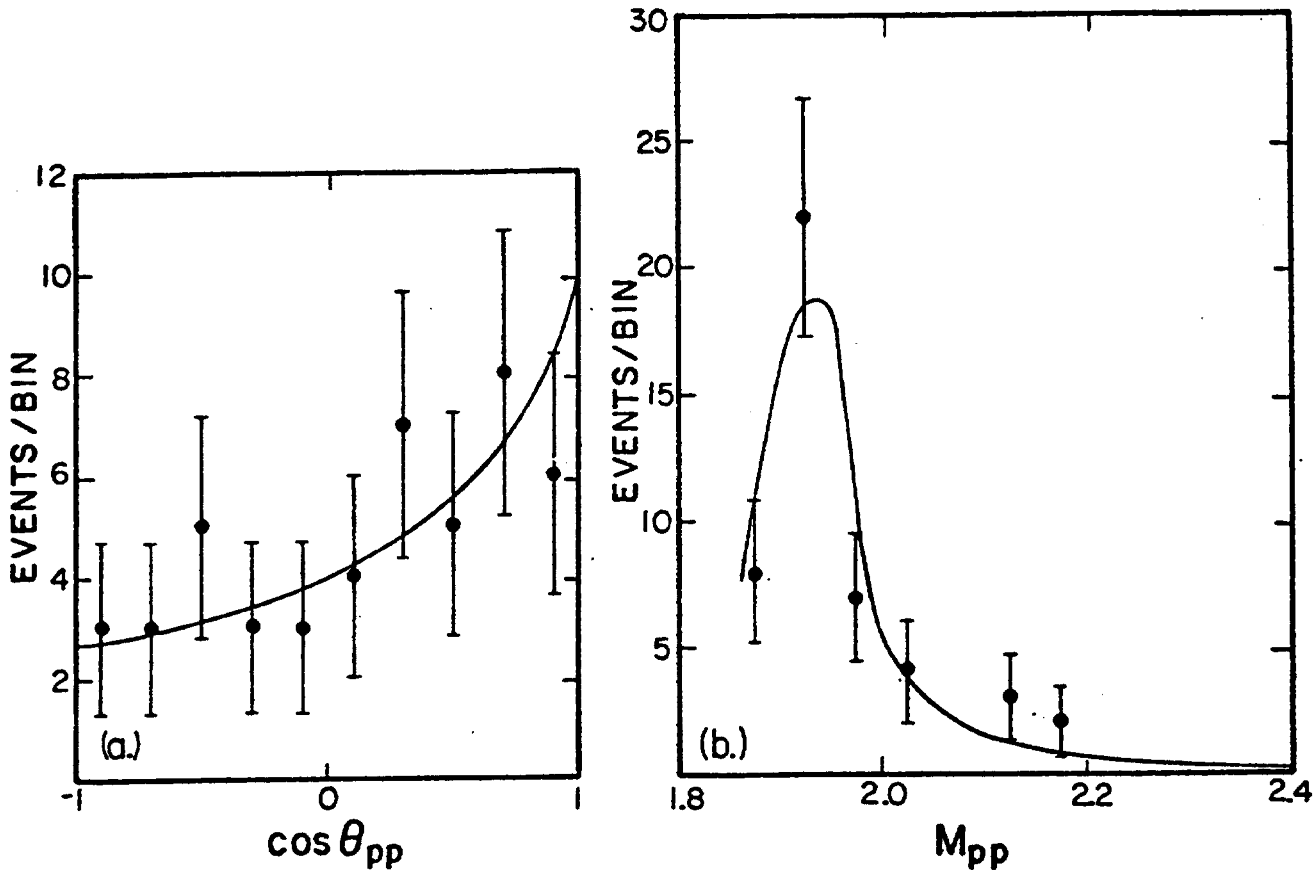

Fig. 4. Analysis of correlations between the two protons in the 2BP-events: (a) - distribution in $\cos\theta_{pp}$ where θ_{pp} is the angle between the protons; (b) - invariant mass M_{pp} distributions for pairs of protons in the 2BP events. Solid lines are handdrawn fits to similar distributions of uncorrelated protons belonging to different events.